GRAvitational-waves Science&technology Symposium (GRASS 2024)
30 September 2024 to 2 October 2024

Contribution of the contrast defect and control sidebands to the phase noise in Advanced Virgo Plus

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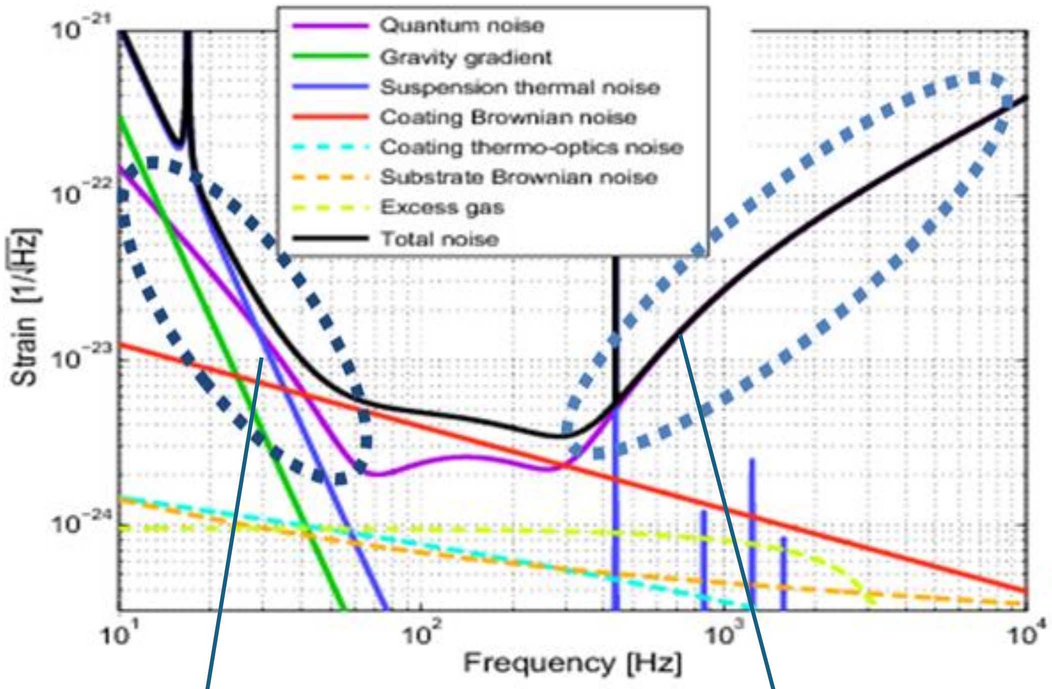
INFN

EGO European Gravitational Observatory
VIRGO Laser Interferometer

Outline

- Introduction to quantum noise and squeezed states in gravitational wave detectors;
- Squeezing angle stabilisation;
- Sources of squeezing angle jitter (phase-noise);
- Contrast defect and control sidebands contribution during O4;
- Comparison with O3;
- Conclusions.

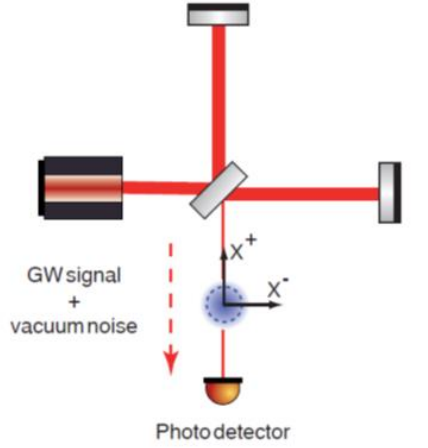
Quantum noise in GW detectors



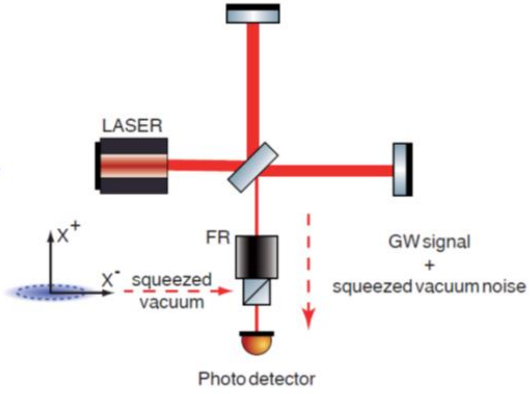
RADIATION PRESSURE NOISE

SHOT NOISE

Quantum noise comes from **vacuum fluctuations** entering the interferometer output port.



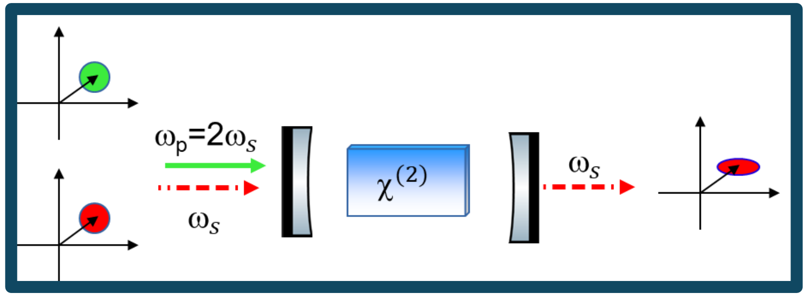
Vacuum squeezed states injection can reduce quantum noise.



C. M Caves. Physical Review D, 23(8):1693, 1981

Squeezed vacuum generation

Optical Parametric Oscillator (OPO)



1985: Squeezing in RADIO-FREQUENCY band

VOLUME 55, NUMBER 22 PHYSICAL REVIEW LETTERS 25 NOVEMBER 1985

Observation of Squeezed States Generated by Four-Wave Mixing in an Optical Cavity

R. E. Slusher
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

L. W. Hollberg
AT&T Bell Laboratories, Holmdel, New Jersey 07733

and

B. Yurke, J. C. Mertz, and J. F. Valley[a]
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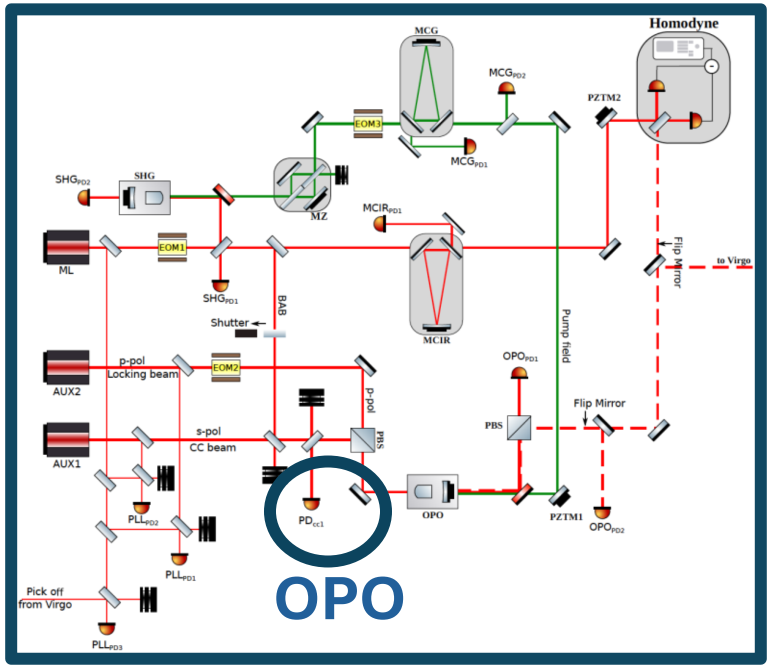
(Received 27 August 1985)



2007: Squeezing in AUDIO-FREQUENCY band

New Journal of Physics
The open-access journal for physics

Quantum engineering of squeezed states for quantum communication and metrology

H Vahlbruch[1], S Chelkowski, K Danzmann and R Schnabel
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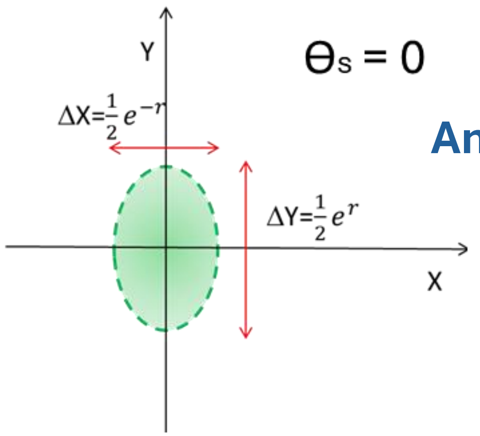
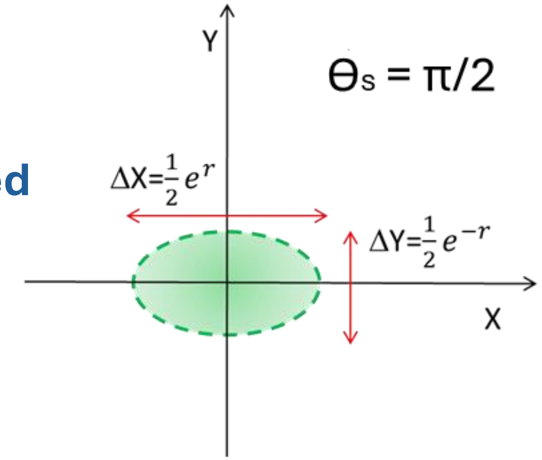
New Journal of Physics **9** (2007) 371
Received 29 August 2007

Squeezed states of light and squeezing angle

Squeezed field are characterized by a reduced uncertainty in amplitude or phase.

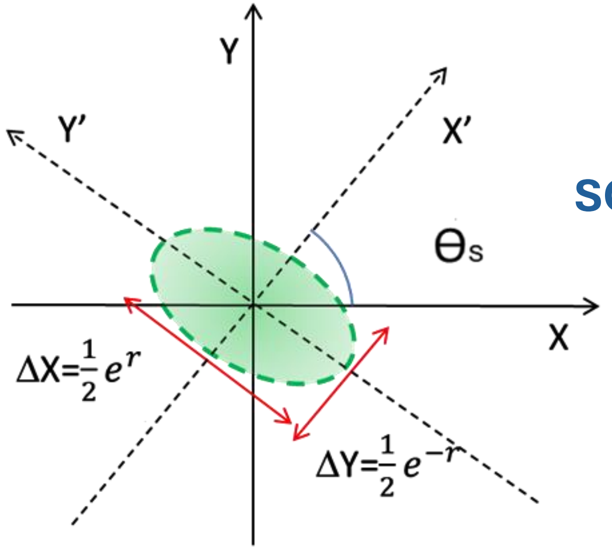


Amplitude-squeezed state



Phase-squeezed state

Generic squeezed state



SQUEEZING ANGLE

It needs to be stabilized in order to have squeezed states useful for gravitational wave detectors.

Need for squeezing angle stabilization

In order to have squeezed states at the frequencies of interest for gravitational wave detector (**audio-band**) it is necessary to stabilize the squeezing angle, being the **measurement times much longer** with respect to those necessary at radio-frequency band.

Squeezing angle Phase-noise ⟺ Angle fluctuations of the squeezing quadrature w.r.t. the measurement quadrature.

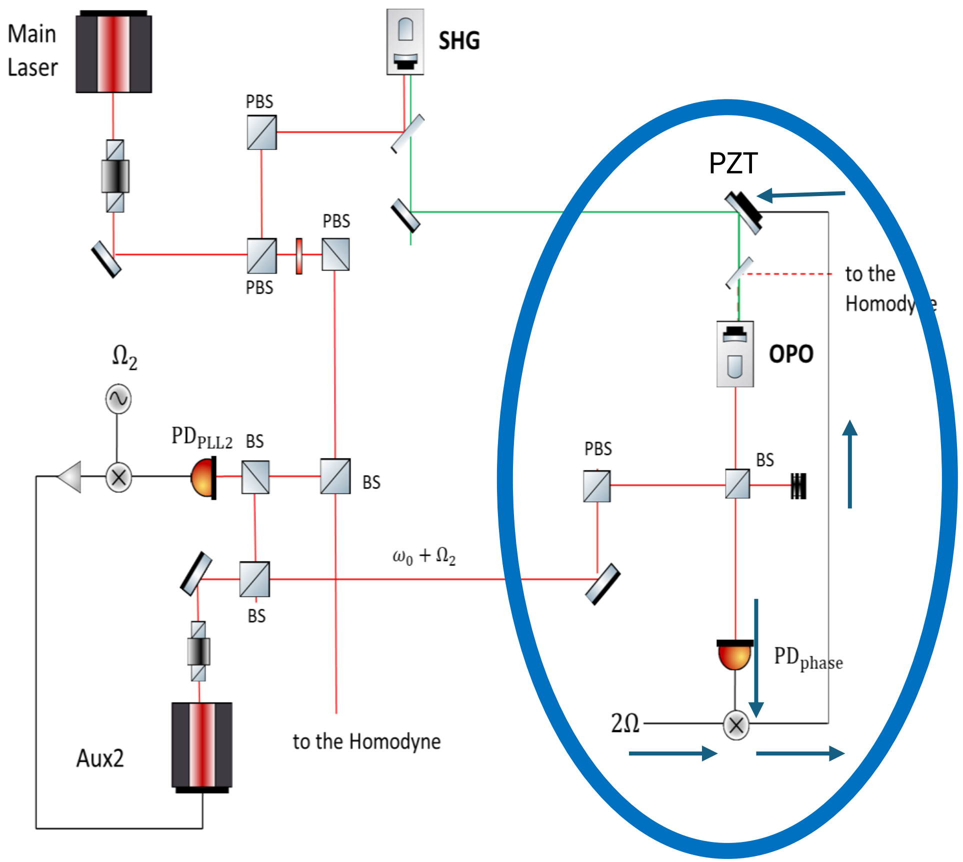
Fluctuations faster than the measurement time → Anti-squeezing and squeezing quadrature coupling → Squeezing degradation

$$V_{\text{tot}}(\theta, \phi_{\text{rms}}) = V(\theta)\cos^2\phi_{\text{rms}} + V(\theta + \pi/2)\sin^2\phi_{\text{rms}}$$

$V(\theta)$ $V(\theta + \pi/2)$ Variance in cosine and sine quadratures

ϕ_{rms} RMS phase noise

Squeezing angle stabilization: coherent control of the pump beam phase

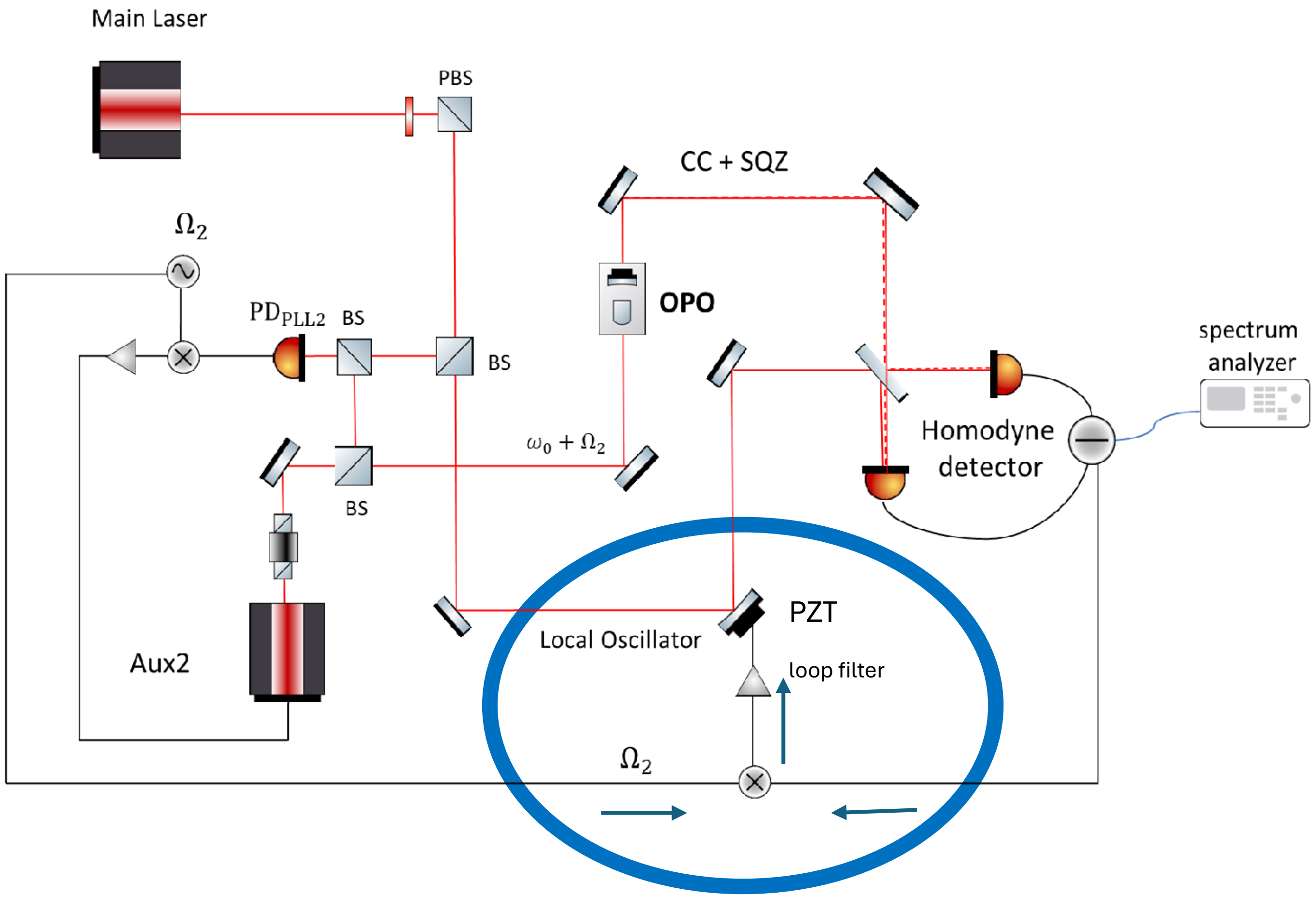


Use of a **coherent control (CC) field with a frequency shift Ω** w.r.t. vacuum squeezed mode such that it can sense the OPO nonlinearity.

This one sideband field is injected inside the OPO and it turns in a two-sideband field (equally shifted w.r.t. to the carrier frequency) with amplified and deamplified quadrature.

Reflected beam **demodulated at 2 Ω,** error signal sent to a piezo-electric actuator along the path of the second-harmonic pump beam, in order to stabilize its phase.

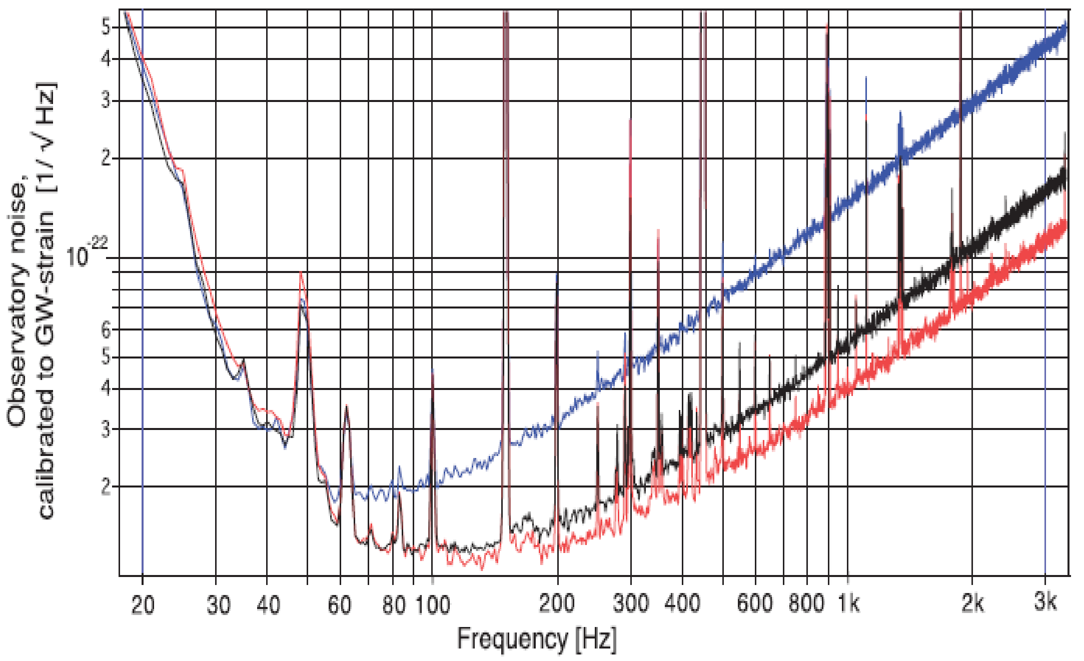
Squeezing angle stabilization: coherent control of the Local Oscillator (LO) beam phase



The **Coherent Control** (CC) beam is partially transmitted by the OPO and it arrive on a 50:50 BS where it **beats with the Local Oscillator (LO) beam**.

The signal of the homodyne detector is **demodulated at Ω**, and an error signal is sent to a piezo-electric actuator along the LO path in order to stabilize the LO phase with respect to the phase of the squeezed beam, being the squeezing angle already stabilized in the previous step.

Squeezing efficency demonstrated in Advanced Virgo



no-squeezing
3.2 ± 0.1 dB squeezing
8.5 ± 0.1 dB anti-squeezing
5% - 8% overall sensitivity improvement of the detector (Binary Neutron Star BNS horizon)
16% - 26% BNS detection rate increase

Physical review letters 123.23 (2019): 231108.

The difference between squeezing level and anti-squeezing is due to phase-noise.

Sources of squeezing angle jitter (phase noise)

From the Squeezer

- OPO cavity length control
- Crystal temperature fluctuations
- ...

Estimated for Advanced Virgo squeezer

$\delta\theta_{SQZ}$ =1.7 mrad

From the interferometer

- Interaction with residual sidebands from OMC
- Contrast defect at the output port
- Higher order modes (Gouy phase)
- Alignment
- Coherent Control loop
- ...

Measured for AdV (O3)

$\delta\theta_{ITF}$ =40 mrad

about **20 mrad from Coherent Control (CC) loop**

8 mrad from 8 MHz and 56 MHz SBs

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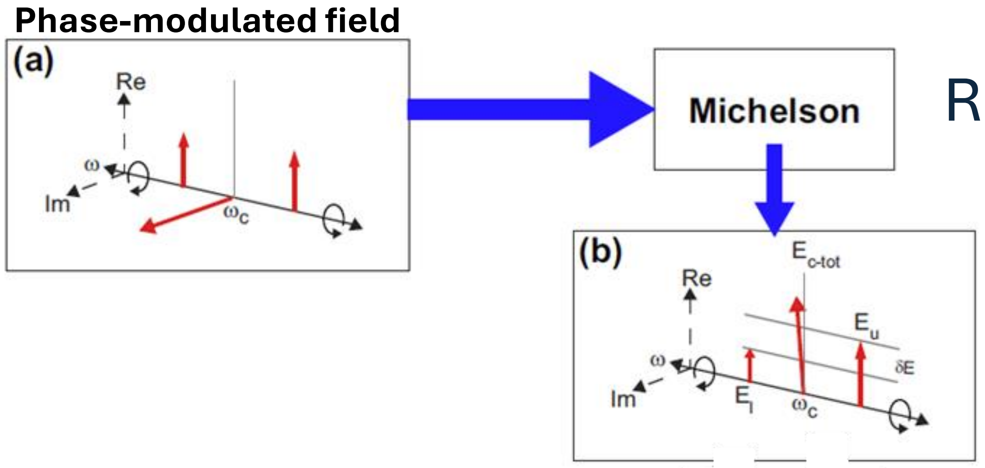
Inferferometer contrast defect

Contrast defect is **due to the asymmetry of the Michelson arm reflectivities and to the reflection beam spatial overlap**. It has the same frequency as the carrier, then it is only spatial-mode attenuated by the Output Mode Cleaner (OMC). It can be measured only sending to zero the dark fringe offset.



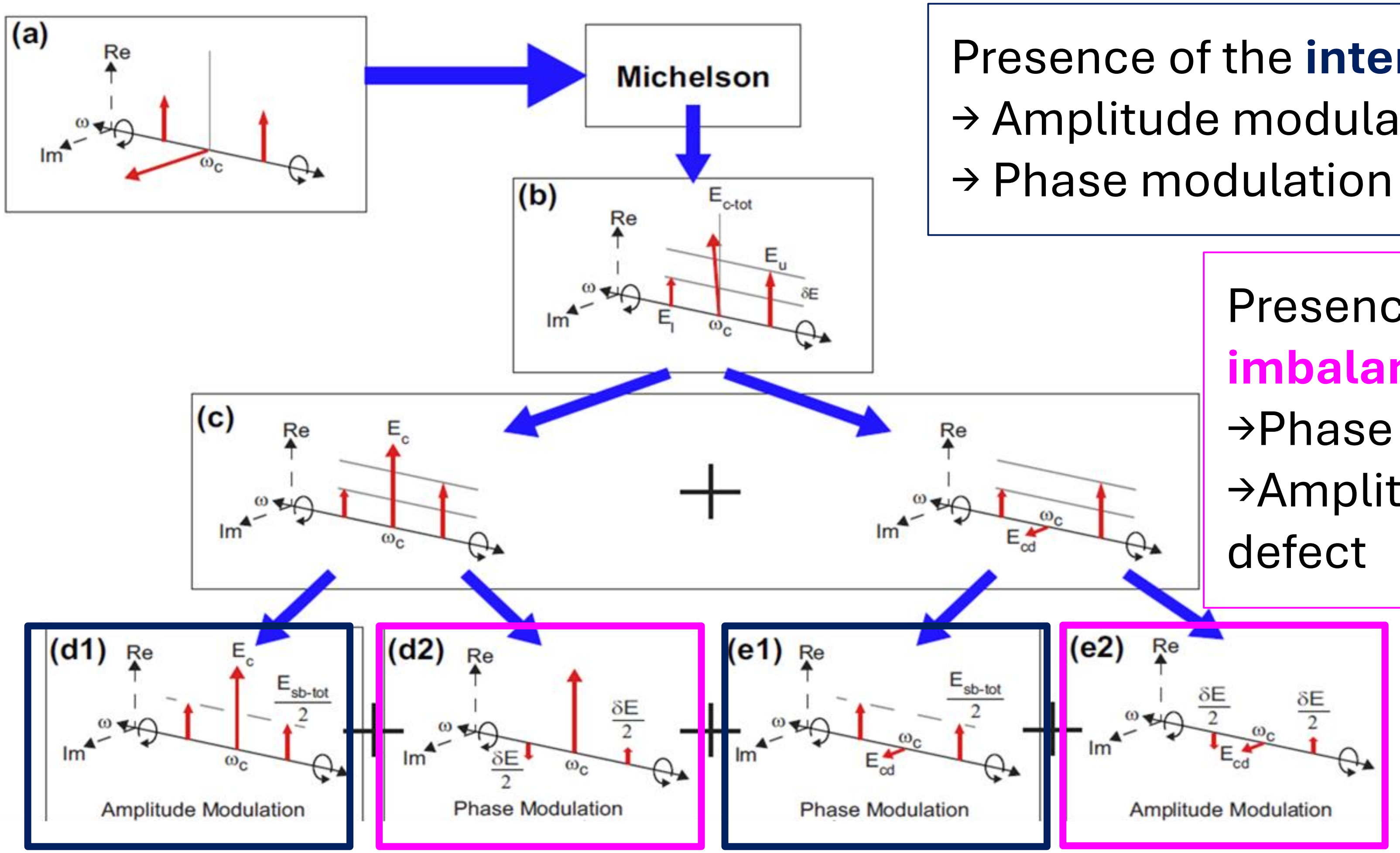
Readout quadrature phase **due to contrast defect**.

$$\phi_{\rm rd} \approx \tan(\phi_{\rm rd}) = \frac{E_{\rm cd}}{E_{\rm c}}$$

Phase fluctuations of these two fields is source of “phase-noise”.

All the contributions, are calculated w.r.t. this angle.

Phase noise due to interferometer control sidebands interacting with the interferometer contrast defect



Presence of the **interferometer control sidebands**:

→ Amplitude modulation of the carrier

→ Phase modulation of the contrast defect

Presence of a **sideband power imbalance**:

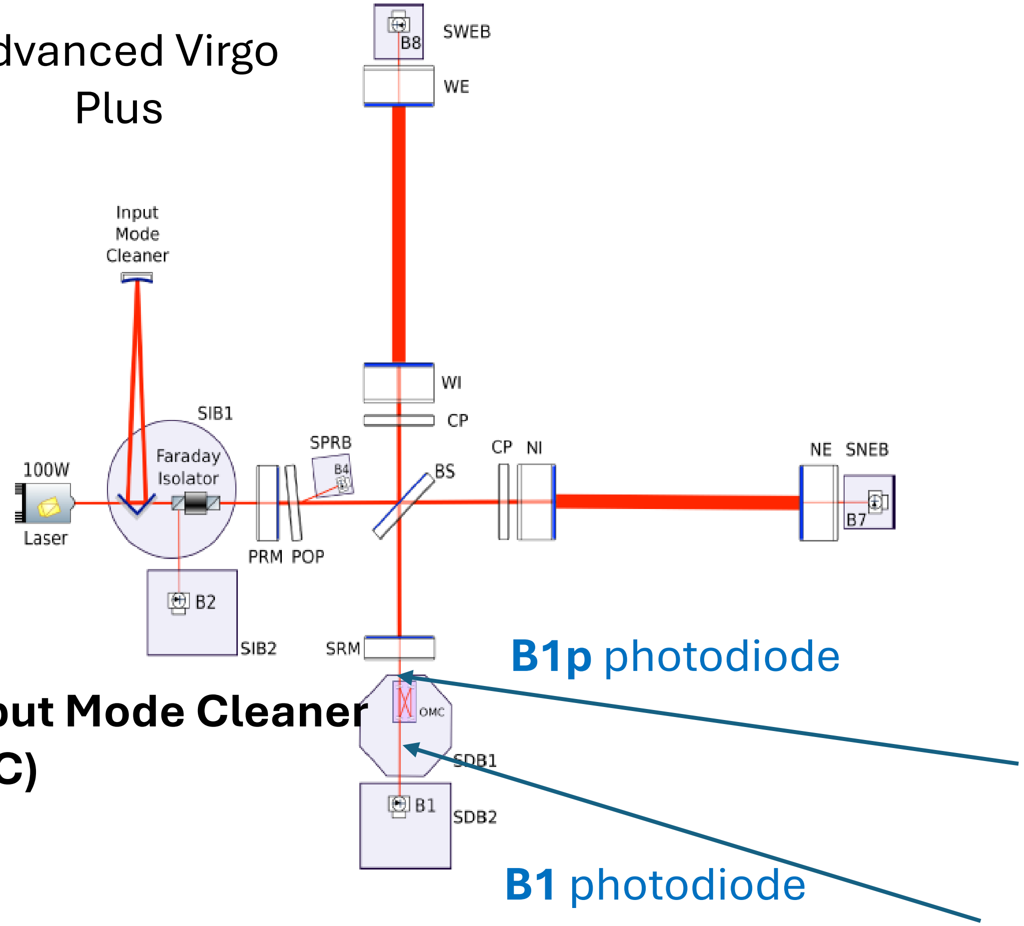
→Phase modulation of the carrier

→Amplitude modulation of the contrast defect

Credits: S. Chua PhD thesis

Phase-noise due to sidebands and their imbalance

Advanced Virgo Plus



Output Mode Cleaner (OMC)

$$\tilde{\theta}_{\mathrm{cd}} = \sqrt{(\tilde{\theta}_{\mathrm{c-AM}})^2 + (\tilde{\theta}_{\mathrm{cd-PM}})^2} = \sqrt{\frac{T_{\mathrm{sb}} 2\bar{P}_{\mathrm{sb}} P_{\mathrm{cd}}}{P_{\mathrm{c}} P_{\mathrm{c-tot}}}}$$

$$\tilde{\theta}_{\mathrm{unb}} = \sqrt{(\tilde{\theta}_{\mathrm{c-PM}})^2 + (\tilde{\theta}_{\mathrm{cd-AM}})^2} = \sqrt{\frac{T_{\mathrm{sb}} (\delta P) P_{\mathrm{cd}}}{P_{\mathrm{c}} P_{\mathrm{c-tot}}}}$$

$\tilde{\theta}_{\mathrm{c-AM}}$ $\tilde{\theta}_{\mathrm{c-PM}}$ $\tilde{\theta}_{\mathrm{cd-PM}}$ $\tilde{\theta}_{\mathrm{cd-AM}}$ — Phase noise contributions due to amplitude and phase modulation of the carrier and of the contrast defect.

P_{c} P_{cd} $P_{\mathrm{c-tot}}$ — Carrier (c) and contrast defect (cd) power, total power at the carrier frequency (c-tot).

$T_{\mathrm{sb}} 2\bar{P}_{\mathrm{sb}}$ δP — Transmitted sideband (sb) power, sb power imbalance.

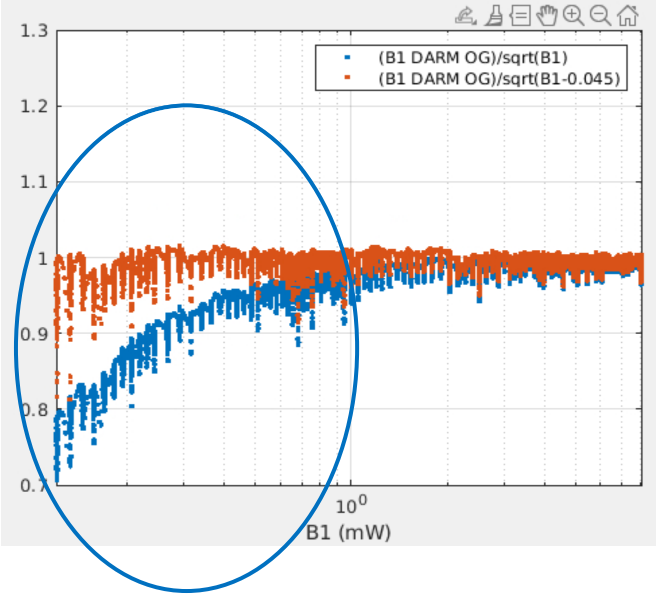
Measurement of the contrast defect

A necessary condition for this measurement is to keep the offset of the DARM degree of freedom to zero (*).

$$\text{DARM} = \frac{L_N - L_W}{2}$$

In this way it is possible to evaluate the discrepancy between the DARM Optical Gain (OG) and the square-root of the power measured with the dark fringe photodiode (B1).

The optical gain is the slope of the error signal used to control DARM d.o.f. and it shoud be equal to sqrt(power on B1).



(*) Actually this condition cannot be perfectly reached, otherwise the interferometer control is lost.

Procedure of the analysis

- Given the contrast defect power estimation, we evaluated the power of carrier and sidebands (6 MHz and 56 MHz) **before** the Output Mode Cleaner (OMC);
- We calculated the **transmission coefficient of the OMC for the sidebands**

Transmission and reflection coeffient of the OMC input and output mirrors

$$T_{SB} = \left| \frac{t_{in} t_{out}}{1 - (1 - \rho) r_{in} r_{out} e^{i2\pi \frac{f_{SB}}{FSR}}} \right|^2$$

SB frequency

losses

O4

Tsb(6 MHz) → **3900 ppm**
Tsb(56 MHz) → **45 ppm**

O3

Tsb(6 MHz) → **29000 ppm**
Tsb(56 MHz) → **192 ppm**

In O3 we had two OMCs each with a finesse of about 125.

Results for O4 and comparison with O3

O4

CD power estimation	Power before OMC	% 56 MHz (Upper SB – Lower SB)	% 6 MHz (Upper SB – Lower SB)	% Carrier	PHASE NOISE 56MHz	PHASE NOISE 6MHz
45 uW	689 mW	6.8% - 6.4%	0.9% - 1.1%	84.8%	**0.058 mrad**	**0.212 mrad**
50 uW	112 mW	20% - 16.3%	1.5% - 1.5%	60.6%	**0.003 mrad**	**0.375 mrad**
70 uW	197.4 mW	11.5% -9.8%	0.9% - 0.7%	77.1%	**0.077 mrad**	**0.204 mrad**

O3

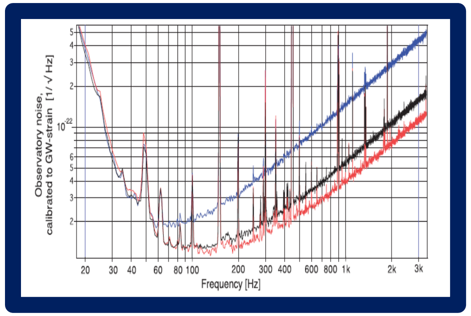
CD power estimation	PHASE NOISE 56MHz
130 mW	**2.6 mrad**
200 mW	**13 mrad**
260 mW	**15 mrad**

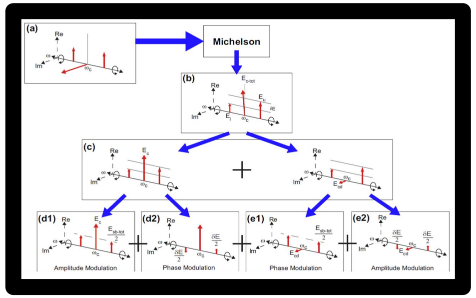
Phase noise contribution due to the interaction of sidebands with contrast defect is much lower in O4 with respect to O3.

https://doi.org/10.1016/j.nima.2024.169629

Conclusions

- Phase noise has a big impact on squeezing degradation;
- There are several sources of phase noise, among them the interaction of control sidebands with the interferometer contrast defect;
- From the analysis of this contribution we deduced that in Advanced Virgo Plus (O4) this it is much reduced with respect to O3 due to a better filtering of the control sidebands.





O4

PHASE NOISE 56MHz
0.058 mrad
0.003 mrad
0.077 mrad

O3

PHASE NOISE 56MHz
2.6 mrad
13 mrad
15 mrad

Thank you for your attention!